Higgs Spin / Mixture Overview

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for

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Higgs Boson Study Group
Snowmass Energy Frontier Workshop

Brookhaven National Laboratory, Upton, NY

From the Princeton workshop and the next steps

- Higgs Snowmass Workshop, 14 – 15 January 2013, Princeton

  http://physics.princeton.edu/indico/internalPage.py?pageId=1&confId=127

- Session on Spin and CP Mixtures
  - Theory overview (Kirill Melnikov)
  - CMS view (Seth Zenz)
  - ATLAS view (Kirill Prokofiev)
  - Lepton / photon colliders: pending contributions (see today)

- Discussed main ideas for Snowmass studies
  - ATLAS+CMS+ have provided good framework for projections
  - Lepton / photon colliders: were seeking active projections

- Next important milestone: have preliminary studies ready by June 15

Two main paths: spin and mixture

- Two main paths to study "H(125)"

  (1) test of exotic spin > 0 assignments / hypothesis testing

  LHC is excluding already $\Rightarrow$ interest may be reducing
  nonetheless, identify benchmark models for comparison

  (2) measure mixture: tensor structure of interactions (spin-0)
  equivalent effective Lagrangian or scattering amplitude approaches

(2a) ZZH, WWH (SM g_1), $Z\gamma H$, $\gamma\gamma H$, ggH (SM g_2), or 0^- (g_4)

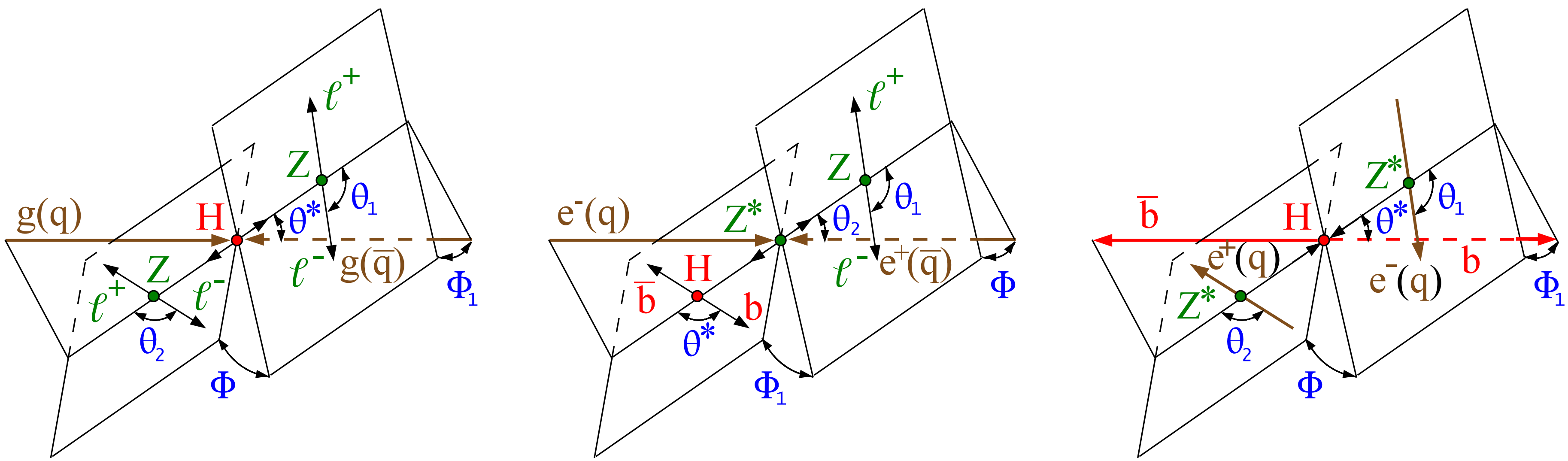
$$A_{VV} \propto \; g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

(2b) $\tau^+\tau^- H, \mu^+\mu^- H, b\bar{b}H, t\bar{t}H, ..$ $\qquad A_{f\bar{f}} \propto \frac{m_f}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1$

(field strength tensor $V^{\mu\nu} \Leftrightarrow f^{(i),\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu$)

“Golden” comparison: pp vs e^+e^-

- LHC: $gg \to H$
- H-factory: $ee \to ZH$
- ILC: $eeZZ \to eeH$



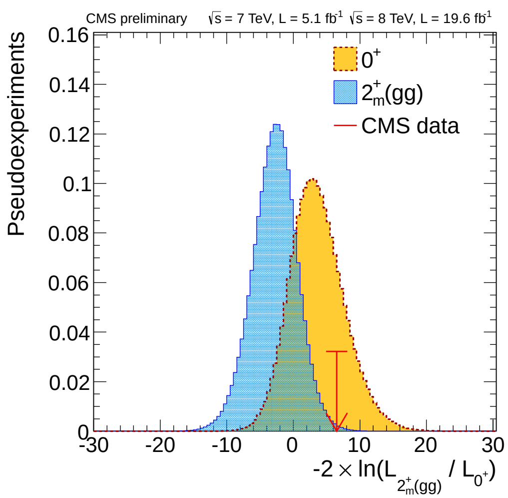
- Golden ZZH coupling as a benchmark (pp vs. H-factory vs. ILC)
  - mostly decay on LHC and production on e^+e^-
  - kinematics: $m(Z_i)$, θ_i, Φ for spin$= 0$; add θ^* and Φ_1 for spin$\neq 0$
  - $m(Z^*) \Leftrightarrow e^+e^-$ threshold scan
  - may combine with WWH, but cannot use $e^+e^-WW \to \nu\bar{\nu}H$
  - no strict boundaries: $Z(W)H$ and VBF contribute to LHC, ILC
  - fermion couplings discussed separately

Path 1: Spin > 0

- Several test models adopted by LHC for ZZH, WWH, $\gamma\gamma H$, ggH

model	X production	comments
0^-	any	pseudoscalar
1^+	$q\bar{q} \to X$	exotic pseudo-vector, not for $\gamma\gamma H$, ggH
1^-	$q\bar{q} \to X$	exotic vector, not for $\gamma\gamma H$, ggH
$2^+_{m\, q\bar{q}}$	$q\bar{q} \to X$	graviton-like tensor with minimal couplings
2^+_m	$gg \to X$	graviton-like tensor with minimal couplings
2^-_h	$gg \to X$	"pseudo-tensor"

- Possible measure tensor structure, less motivated
  - for Snowmass may stick to a few benchmark models (e.g. above)



- LHC: MELA / BDT techniques, example:

CMS expect (observe) 2^+_m vs SM 0^+: 1.9σ (2.7σ)

scales to 300/fb LHC $\sim$10σ

Path 2: Mixture in VVH

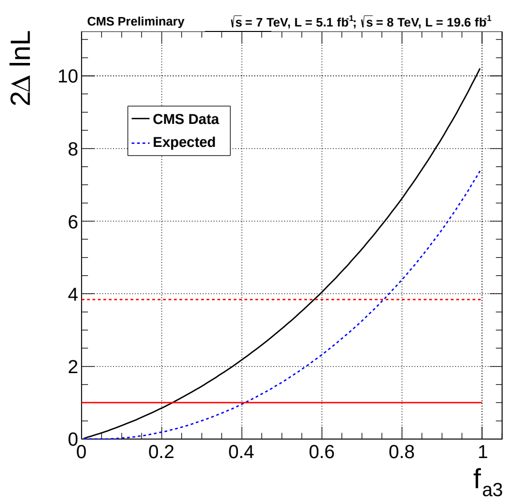
ZZH, WWH (SM g_1), $Z\gamma H$, $\gamma\gamma H$, ggH (SM g_2), or 0^- (g_4)

$$A_{VV} \propto \; g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

When g_1 dominates, f_{g_4} is CP-violating fraction (here $g_i = 1 \leftrightarrow \sigma_i$):

$$f_{CP} = f_{g4} = \frac{|g_4|^2\sigma_4}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}\,; \qquad \phi_{g4} = \arg\left(\frac{g_4}{g_1}\right)$$

$$f_{g2} = \frac{|g_2|^2\sigma_2}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}\,; \qquad \phi_{g2} = \arg\left(\frac{g_2}{g_1}\right)$$



- LHC: assuming SM and ignoring g_3

CMS expect (observe) $f_{CP} = 0.00 \pm 0.40$ (± 0.23)

scales to 300/fb LHC $f_{CP} = 0.00 \pm 0.08$

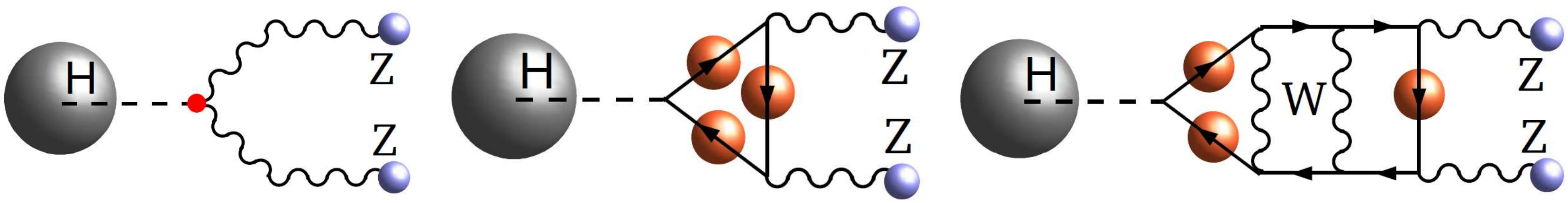
may include f_{g2} in projections

Mixture in VVH

- Amplitude for $X_{J=0} \to V_1 V_2$

$$A = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

- SM Higgs 0^+: (a_1) CP $\sim$few% (a_2) CP $\sim 10^{-10}$? (a_3) $\cancel{CP}$



(or beyond SM) (or beyond SM)

- 3 amplitudes ("experiment") $\Leftrightarrow$ 3 coupling constants ("theory")

$$A_{00} = -\frac{m_H^2}{v} \left(a_1 x + a_2 \frac{m_1 m_2}{m_H^2} (x^2 - 1) \right)$$

$$A_{\pm\pm} = +\frac{m_H^2}{v} \left(a_1 \pm i a_3 \frac{m_1 m_2}{m_H^2} \sqrt{x^2 - 1} \right)$$

$$x = \frac{m_H^2 - m_1^2 - m_2^2}{2 m_1 m_2}$$

Photon and Muon Colliders

- Polarized beams on $\mu^+\mu^-$ and $\gamma\gamma$ colliders with s-channel production
  - would allow to measure A_{++} vs A_{--} amplitudes $\Rightarrow$ CP fraction
  - benchmark measurements f_{CP} in $\mu^+\mu^- H$ and $\gamma\gamma H$
    (not "easily" possible on LHC and e^+e^-)

- even if present, CP violation may be suppressed in ZZH coupling
  - if 0^- coupling to ZZ (same for WW) is suppressed
    ttH, $\tau\tau H$, $Z\gamma H$ may have large CP-violation on LHC and e^+e^-
    small-f_{CP} & large-precision vs large-f_{CP} & smaller-precision
  - $\mu^+\mu^- H$ and $\gamma\gamma H$ would become key measurements on $\mu\mu$ and $\gamma\gamma$

- Feasibility study from $\mu\mu$ and $\gamma\gamma$ collider communities
  - need common convention for the quoted measurement

Path 2: Mixture in $f\bar{f}H$

- Mixture $\tau^+\tau^-H, \mu^+\mu^-H, b\bar{b}H, t\bar{t}H$ harder to measure on $e^+e^-\&\, pp$
  - possible if polarization of fermion decay (production) is measured
    $e^\pm$ beam polarization may help
  - feasibility in $H \to \tau^+\tau^-$
  - feasibility in $e^+e^-(pp) \to t\bar{t}H$
- Similar parameterization:

$$A_{f\bar{f}} \propto \frac{m_f}{v}\bar{u}_2\left(\rho_1 + \rho_2\,\gamma_5\right)v_1 = \frac{m_f}{v}\bar{u}_2\,\rho\left(\cos\theta + e^{i\phi_{\rho 2}}\sin\theta\,\gamma_5\right)v_1$$

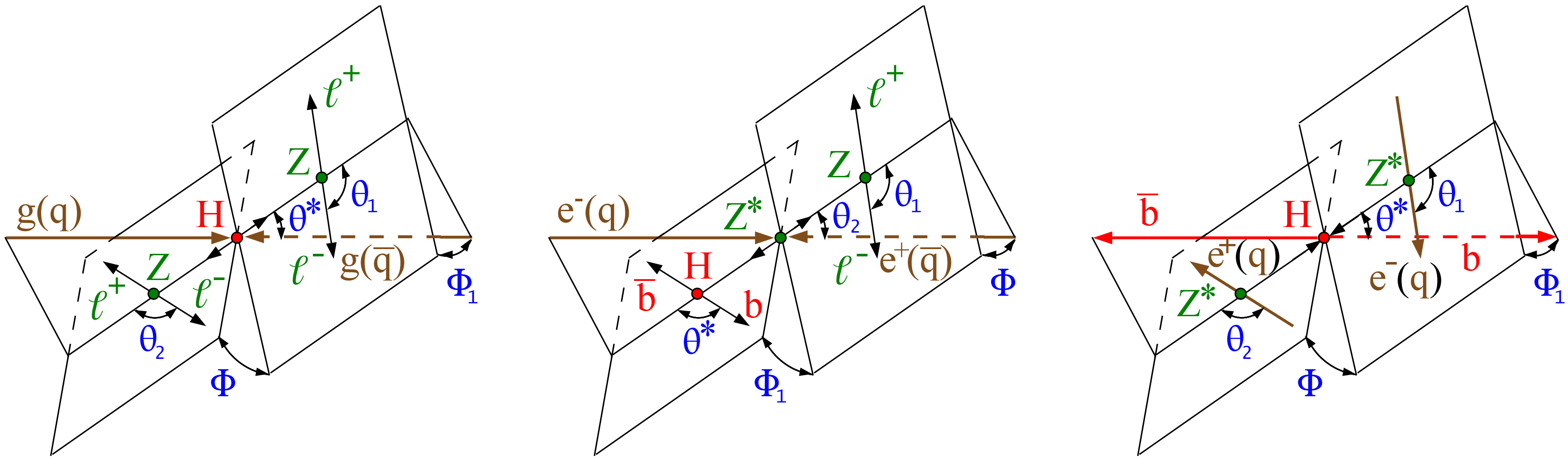
$$f_{CP} = f_{\rho 2} = \frac{|\rho_2|^2\sigma_2}{|\rho_1|^2\sigma_1 + |\rho_2|^2\sigma_2} = \frac{1}{|\rho_1/\rho_2|^2\,\sigma_1/\sigma_2 + 1} = \frac{1}{|\cot\theta|^2\,\sigma_1/\sigma_2 + 1}$$

$$\phi_{\rho_2} = \arg\left(\frac{\rho_2}{\rho_1}\right)$$

- deduce from fermion polarization: $A_{\pm\pm} \propto (\rho_2 \pm \beta\rho_1)$

Possible matrix for pp vs. H-factory vs. ILC

- LHC: $gg \to H$
- H-factory: $ee \to ZH$
- ILC: $eeZZ \to eeH$



	LHC 300/fb	LHC 3000/fb	e^+e^- 250 GeV	e^+e^- 1 TeV
spin-2 Grav. ...	$\sim 10\sigma$ ...	$\gg 10\sigma$ ...	? ...	? ...
f_{CP} in ZZH	± 0.08	± 0.03 (?)	?	?
f_{CP} in $\tau\tau H$	?	?	?	?
f_{CP} in ttH	?	?	–	?
f_{CP} in $Z\gamma H$	?	?	?	?

Summary: Spin and Mixture for Snowmass-2013

- We already know many things, but need to focus on projections:
  - VVH $(V=W,Z)$ couplings at LHC reasonably well covered
  - e^+e^- expectations and fermion couplings need to quantify better
  - quantify $\mu^+\mu^- \to H$ and $\gamma\gamma \to H$ feasibility of CP measurements

	LHC 300/fb	LHC 3000/fb	e^+e^- 250 GeV	e^+e^- 1 TeV	$\mu^+\mu^-$ 125 GeV	$\gamma\gamma$ 125 GeV
spin-2 Grav. ...	$\sim 10\sigma$ ...	$\gg 10\sigma$ ...	? ...	? ...	? ...	? ...
f_{CP} in VVH	± 0.08	± 0.03 (?)	?	?	?	?
f_{CP} in $\tau\tau H$	?	?	?	?	?	?
f_{CP} in ttH	?	?	–	?	–	–
f_{CP} in $\mu\mu H$	–	–	–	–	?	–
f_{CP} in $\gamma\gamma H$	–	(?)	–	–	–	?

ONE-SLIDE CONTRIBUTIONS

ATLAS Snowmass Spin/CP studies

- Moriond results suggest the dominant spin-parity $J^P=0^+$: ATL-CONF-2013-013, ATL-CONF-2013-029, ATL-CONF-2013-031, CMS-CMS-PAS-HIG-13-002, CMS-PAS-HIG-13-003.

- Snowmass study: sensitivity to CP-mixing, anomalous couplings in $H \to ZZ^{(*)} \to 4l$.
  - As for the European strategy: generator level + smearing to accommodate for detector effects, event weights for trigger and lepton reconstruction efficiency.

$$A(X \to VV) \sim (\underbrace{a_1 M_X^2 g_{\mu\nu}}_{\text{CP-even}} + \underbrace{a_2 (q_1+q_2)_\mu (q_1+q_2)_\nu}_{\text{CP-even}} + \underbrace{a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta}_{\text{CP-odd}}) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

- Available Monte Carlo generators:
  - JHU (LO): allows to vary a_1, a_2, a_3 independently.
  - MadGraph 5 + aMC@NLO: introduces a single mixing angle between the 1st and the 3d components of the amplitude.

- Monte Carlo re-weighting: available in JHU (ratio of $|M|^2$); can be introduced in MG5 and aMC@NLO (pre-defined set of weights corresponding to different mixing).

- Observables: it is probably most interesting to estimate the sensitivity to the mixing angle between 1st and the 3d components and possibly to the phase. f_{a3}?

- Study methods: Matrix element likelihood fit with free parameters, Modeling mixing strength by re-weighting and comparing with $J^P=0^+$, Optimal observables analysis, Angular asymmetries.

- Given there is enough taskforce, we can add study of the VBF forward jets and fermionic channels: $H \to \tau\tau/\mu\mu$.

Submitted by K. Prokofiev (NYU)

Spin-CP studies of the new boson for Snowmass

Study kinematic distributions of X->VV->4 fermions to extract tensor amplitude structure of production and decay of the new boson.

using JHU generator and MELA method:

- http://www.pha.jhu.edu/spin/
- Phys. Rev. D 81, 075022 (2010)
- Phys. Rev. D 86, 095031 (2012)

Evaluate the sensitivity at future pp and (possibly) e+e- colliders for:

(gen-level studies with smearing+acceptance cuts)

❑ CP mixing studies assuming spin 0

$$A(X_{J=0} \to V_1 V_2) = v^{-1} \left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

with present LHC statistics pure 0- ruled out (g_i=0 for i≠4) -> next steps

- test mixed hypotheses with more than one g_i≠0 (with interference included)
- fit directly the fractions and phases of g_i from kinematic distributions

  Eg: 0.08 precision expected on g_4 fraction with 300 fb^{-1} at LHC

❑ Exotic spin scenarios

(similar, more complex, formula as above available in cited papers for spin>0)

most basic (minimal couplings) scenarios under test at LHC -> next steps

- test wide range of scenarios (identify the ones with kinematics very similar to 0+ SM case)
- more model independent approach: production-independent spin tests

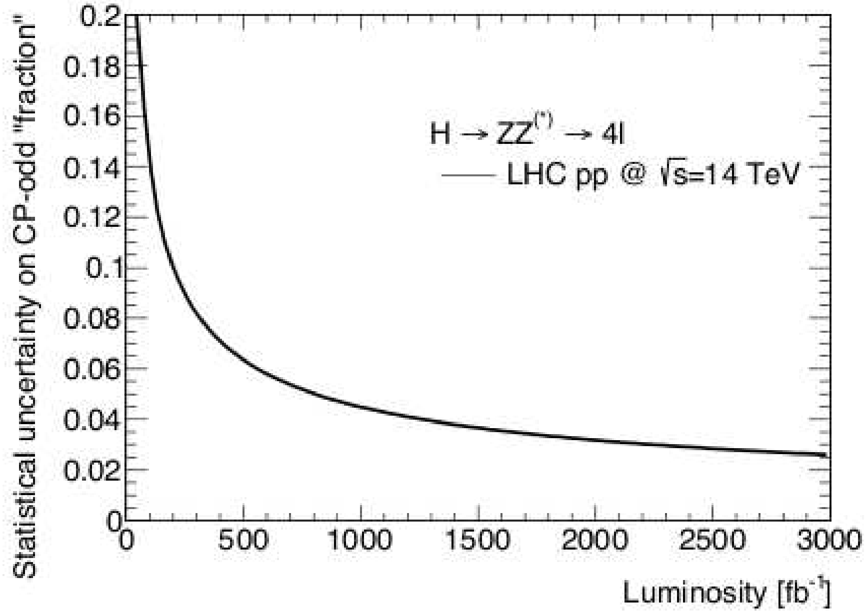
  mixing-independent spin tests

Main contributors: S.Bolognesi[1], Y.Gao[2], N.Tran[2], A.Whitbeck[1] (1= Johns Hopkins, 2=FNAL)

E. Feng (ANL): Higgs CP Fraction

- Matrix element method to measure spin, CP, and couplings in H->ZZ->4l
  - Unbinned maximum likelihood fit to analytical prediction using 3 masses (m_{4l}, m_{12}, m_{34}) and 5 angles ($\cos(\theta^*)$, ϕ_1, $\cos(\theta_1)$, $\cos(\theta_2)$, $\Delta\phi$) from 4 leptons
- Characterize sensitivity to CP-odd fraction projected onto H->ZZ final state by fitting to linear combination of 0^+ and 0^- hypotheses as function of 14 TeV lumi
- CP-odd component corresponds to non-zero $g_4^{(0)}$ form factor in ME:

$$A(X\to V_1V_2) = v^{-1}\Big(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\Big),$$



- Statistical uncertainty of ~8% (3%) can be achieved with 300 (3000) fb^{-1} at 14 TeV
  - Includes detector acceptance
  - Generating fastsim for systematics, which should be relatively small
- Additional studies may include non-minimal couplings for spin-2, but lower sensitivity

ζ_2 is the degree of circular polarization

(ζ_3, ζ_1) are the degrees of linear polarization

Only with C

In s-channel production of Higgs:

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2}\left\{[1+\zeta_2\bar{\zeta}_2] + \mathcal{A}_1\left[\zeta_2+\bar{\zeta}_2\right] + \mathcal{A}_2\left[\zeta_1\bar{\zeta}_3+\zeta_3\bar{\zeta}_1\right] - \mathcal{A}_3\left[\zeta_1\bar{\zeta}_1-\zeta_3\bar{\zeta}_3\right]\right\}$$

== 0 if CP is conserved

== +1 (-1) for CP is conserved for A CP-Even (CP-Odd) Higgs

If $\mathcal{A}1\neq0$, $\mathcal{A}2\neq0$ and/or $|\mathcal{A}3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

Possible to search for CP violation in Ž H Ž fermions without having to measure their polarization

In bb, a ≤1% asymmetry can be measure with 100 fb-1 that is, in 1/2 years

arXiv:0705.1089v2

Submitted by M. Velasco (NWU)